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ESTIMATES OF BLOWDOWN OF QUASI-STATIC PRESSURES IN VENTED CHAMBERS

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ESTIMATES OF BLOWDOWN OF QUASI-STATIC PRESSURES IN VENTED CHAMBERS

by

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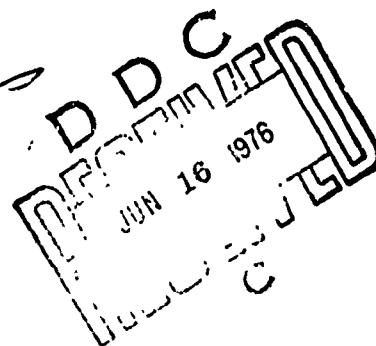
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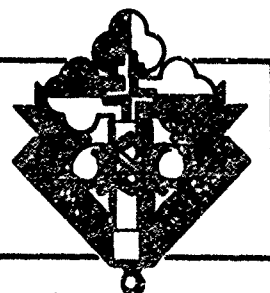Post Office Drawer 28510, 8500 Culebra Road

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

   This report presents recent analyses, and fits of experimental data to scaled parameters, for blowdown pressures in vented chambers. Theoretical predictions are made for time histories of blowdown pressures, and a scaling law is presented. Limited comparisons are made with experiment.

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SUMMARY

This report presents recent analyses, and fits of experimental data to scaled parameters, for time histories of the relatively long duration pressures which exist after explosions in vented chambers. A convenient form for combination of several scaled quantities arises from the analysis. Curves of vent pressure time histories and durations presented in the report should, however, be considered as tentative because of additional current work on vented gas pressures in the Edgewood Arsenal suppressive structures program.

PREFACE

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

ESTIMATES OF BLOWDOWN OF QUASI-STATIC PRESSURES IN VENTED CHAMBERS

I. INTRODUCTION

In earlier work on estimating quasi-static pressures within vented structures, a dimensional analysis was made and scaled curves generated based on empirical fits to data for peak quasi-static pressures and blowdown times (see Fig. B5 and B6 in Ref. 1). Data from References 2 and 3 were fitted to an empirical combination of scaled parameters which seemed to fit the data best.

To describe more completely the internal pressures applied to vented structures during the blowdown of these relatively long-term pressures (long term compared to initial reflected shock pressures), it would be desirable to be able to estimate the time histories, including their character for structures which were better vented than those reported in References 2 and 3. Reference 3 reports some data for impulse in the quasi-static phase, as well as peak quasi-static pressure and blowdown times. These authors (Keenan and Tancreto) also note that they obtained no measurable quasi-static pressure rises for values of $(A_{vent}^{3/2}/V)$ of 0.678 or greater. No measurements have apparently been made in the range

$$0.0775 \leqslant \left(\frac{A_{vent}^{3/2}}{V} \right) \leqslant 0.678$$

This report includes additional studies on blowdown of pressures resulting from explosions in vented structures, with particular emphasis on prediction of the details of these pressures for design of suppressive structures. The work was performed for the Edgewood Arsenal suppressive structures program under Contract DAAA15-75-C-0083.

II. THEORY

An Analysis is available in the literature which can be applied with some modification to this problem. Owczarek,[4] on pp. 254-255, considers the problem of prediction of pressure with time in a tank initially filled with gas at high pressure, and then emptied by the sudden opening of a convergent nozzle in the tank wall. He assumes* a quasi-steady flow process, a perfect gas, no heat transfer, and isentropic expansion in the nozzle. Two flow regimes apply, for back pressure p_0 less than, and equal to or greater than, critical pressure for the nozzle. Schematically, this situation is shown in Figure 1.

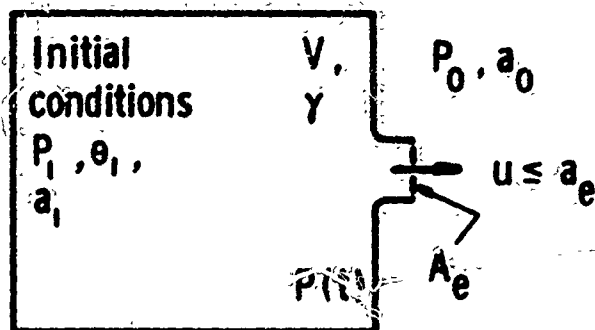*Elsewhere in Reference 4, Owczarek also considers this same problem with shocks and rarefactions in the tank.

FIGURE 1. IDEALIZED VESSEL BLOWDOWN

Owczarek's solutions give time t as a function of ratio of pressure at this time to outside ambient pressure.[†]

$$\overline{P}(t) = \frac{P(t)}{p_o} \tag{1}$$

These solutions are:

$$t = \frac{V}{A_e (\gamma R_* \theta_1)^{1/2}} \frac{2}{(\gamma - 1)} \left(\frac{\gamma + 1}{2} \right)^{(\gamma + 1)/[2(\gamma - 1)]} \left[\left(\frac{P_1}{P(t)} \right)^{(\gamma - 1)/\gamma} - 1 \right] \tag{2}$$

$$\text{for } P(t) \geqslant p_o \bigg/ \left(\frac{2}{\gamma + 1} \right)^{\gamma/(\gamma - 1)} \tag{3}$$

and

$$t - t_* = \frac{2}{\gamma - 1} \left[\frac{V}{A_e} \left(\frac{\gamma - 1}{2} \right)^{1/2} \frac{\overline{p}^{(\gamma - 1)/(2\gamma)}}{(\gamma R_* \theta_1)} \right] \left[0.4932 \right.$$

$$\left. - \frac{x}{8}(2x^2 + 5)(x^2 + 1)^{1/2} - \frac{3}{8} \ln \left(x + \sqrt{x^2 + 1} \right) \right] \tag{4}$$

for

$$1 \leqslant P \leqslant \frac{1}{\left(\dfrac{2}{\gamma + 1} \right)^{\gamma/(\gamma - 1)}} \tag{5}$$

In Eq. (4), t_* is the time at which P first equals the upper limit in Eq. (5), and x is a dimensionless group

$$x = \left[P^{(\gamma - 1)/\gamma} - 1 \right]^{1/2} \tag{6}$$

[†]In this analysis, all pressures are *absolute* pressures.

8

In these equations, A_e is exit area of the nozzle; the symbol "a" indicates sound velocity, γ is ratio of specific heats for gas within the chamber, R_* is the universal gas constant, and other quantities have been defined. The perfect gas law requires that

$$a^2 = \frac{\gamma P}{\rho} = \gamma R_* \theta \tag{7}$$

So the quantity

$$(\gamma R_* \theta_1)^{1/2} = a_1 \tag{8}$$

i.e., the initial sound velocity within the vessel. The set of Eqs. (2) and (4) applies *only* for initial pressure ratio $\overline{P}_1$ greater than the limit in Eq. (5).

With some assumptions, adaptation and rearrangement, we can apply Owczarek's equations to venting of suppressive structures. Let us assume that the nozzle exit area

$$A_e = \alpha_c A_s \tag{9}$$

The inlet sound velocity a_1 is an important parameter in Eqs. (2) and (4). In suppressive structures, this is not known exactly because the gas being vented is heated air mixed with explosion products. But, from work of Proctor and Filler;[2] it is apparent that the great majority of the pressure rise within a vessel containing an explosion is caused by addition of the heat energy of the explosive to air, rather than addition of mols of explosive products. Assuming that no appreciable venting occurs during the initial stages with shock reflections, this process represents a constant volume heat addition. Such a process raises the absolute temperature of a perfect gas in direct proportion with the absolute pressure rise. From Eq. (3), we then see that

$$\left(\frac{a_1}{a_0}\right) = \left(\frac{T_1}{T_0}\right)^{1/2} = \left(\frac{P_1}{P_0}\right)^{1/2} \tag{10}$$

Equations (2) and (4) can be rearranged in dimensionless form. Let:

$$\overline{\tau} = \frac{t A_e a_1}{V} = \left(\frac{t a_1}{V^{1/3}}\right) \left(\frac{A_e}{V^{2/3}}\right) \tag{11}$$

where $\overline{\tau}$ is a dimensionless time. Then, Eqs. (2) and (4) become

$$\overline{\tau} = \frac{2}{(\gamma-1)} \left(\frac{\gamma+1}{2}\right)^{(\gamma+1)/[2(\gamma+1)]} \left[\left(\frac{P_{c1}}{P}\right)^{(\gamma-1)/(2\gamma)} - 1\right] \tag{2a}$$

$$\text{for } \overline{P} \geqslant 1/\left(\frac{2}{\gamma+1}\right)^{\gamma/(\gamma-1)}$$

9

and

$$\bar{\tau} - \bar{\tau}_* = \left(\frac{2}{\gamma-1}\right)^{1/2} \bar{P}_1^{(\gamma-1)/(2\gamma)} \left\{0.4932 - \frac{x}{8}(2x^2 + 5)(x^2 + 1)^{1/2}\right.$$

$$\left. - \frac{3}{8}\ln\left[x + (x^2 + 1)^{1/2}\right]\right\} \tag{4a}$$

These equations express dimensionless time as a function of dimensionless pressure and ratio of specific heats. They are explicit and allow solution for any initial pressure ratio $\bar{P}_1$ and γ. Plots are shown for a range of $\bar{P}_1$ and $\gamma = 1.4$ in Figures 2 and 3. From these figures, one can see that $\bar{P} = 1$ for finite values of $\bar{\tau}$, i.e., blowdown times are finite. Scaled durations of blowdown $\bar{\tau}_{max}$ can be obtained from Eq. (2a) and (4a) for any $\bar{P}_1$ by determining $\bar{\tau}_x$ and setting $x = 0$. Values for scaled duration of blowdown, $\bar{\tau}_{max}$, and time to reach critical pressure $\bar{\tau}_*$, are shown in Figure 4 as functions of $\bar{P}_1$.

These equations change the definition of $\bar{\tau}$ in Eq. (11) to

$$\bar{\tau} = \left(\frac{\alpha_e A_s}{V^{2/3}}\right)\left(\frac{P_1}{p_0}\right)^{1/2}\left(\frac{t a_0}{V^{1/3}}\right) \tag{12}$$

where a_0 is sound velocity in the outside air, A_s is internal surface area of the structure, and α_e is as defined in Reference 1. From Figure 4 and our previous discussion, we note that $\bar{\tau}_{max}$ is a unique function of $\bar{P}_1$, say

$$\bar{\tau}_{max} = f_1(\bar{P}_1) \tag{13}$$

However, from Eq. (12)

$$\bar{\tau}_{max} = \frac{\bar{\tau}_{max}}{\bar{P}_1^{1/2}} = f_2(\bar{P}_1) \tag{14}$$

Furthermore, we can define a simpler combination of parameters as a scaled time, i.e.,

$$\bar{t} = \left(\frac{t a_0}{V^{1/3}}\right) \tag{15}$$

so that

$$\bar{\tau}_{max} = \left(\frac{\alpha_e A_s}{V^{2/3}}\right)\bar{t}_{max} = f_2(\bar{P}_1) \tag{16}$$
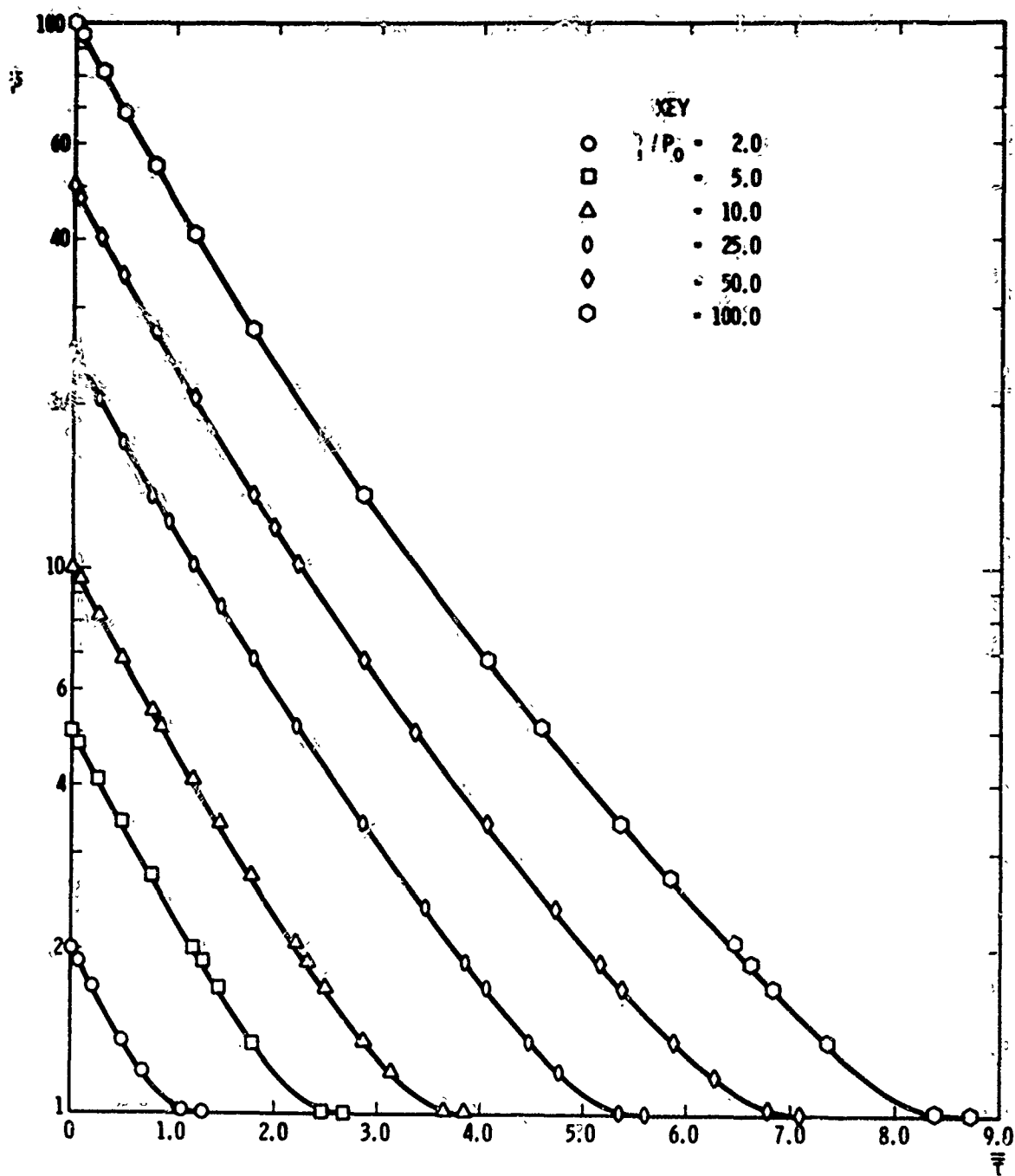
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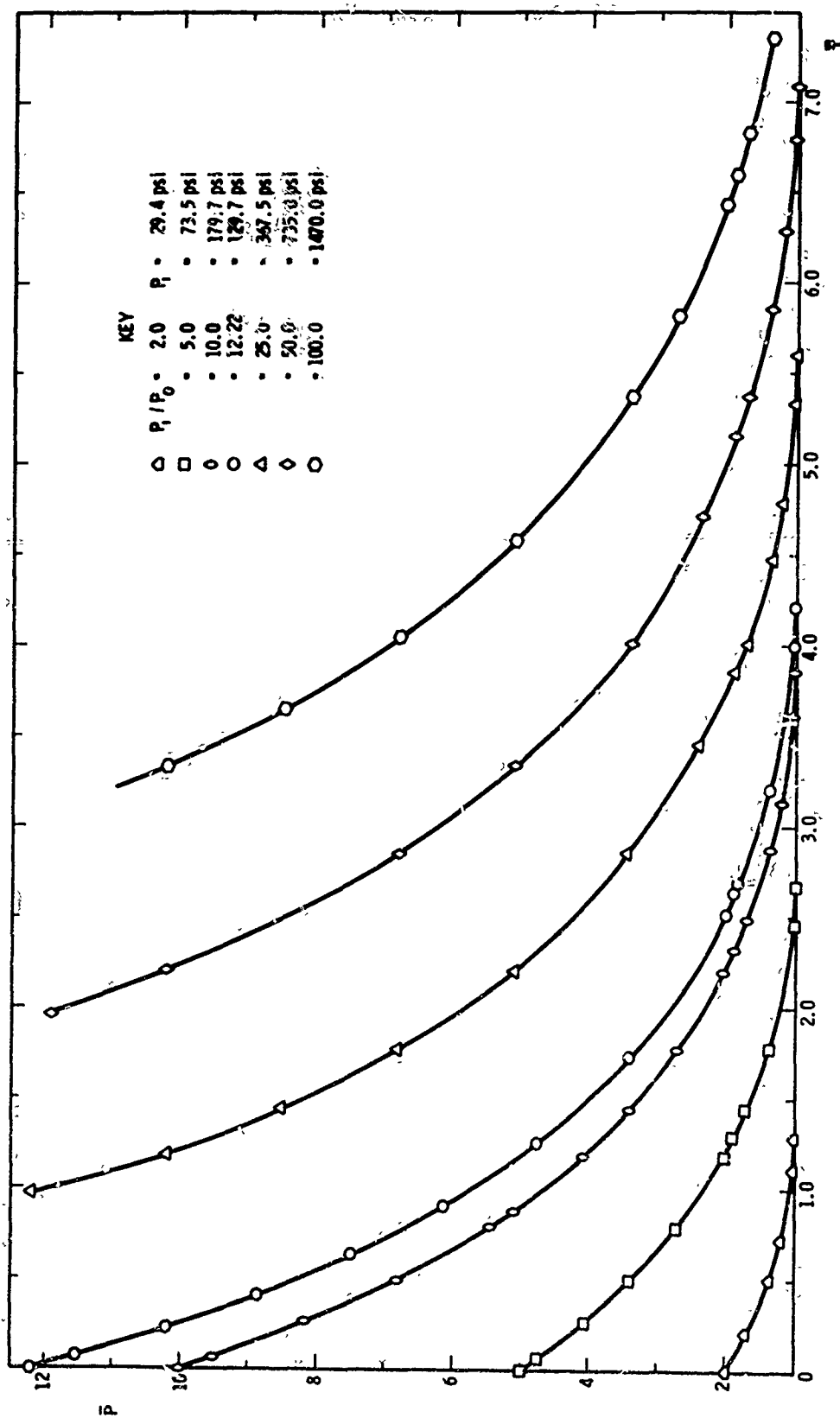FIGURE 2 SEMI-LOG PLOT OF SCALED BLOWDOWN PRESSURE VERSUS SCALED TIME, $\gamma = 1.4$

FIGURE 3. LINEAR PLOT OF SCALED BLOWDOWN PRESSURE VERSUS SCALED TIME; $\gamma = 1.4$
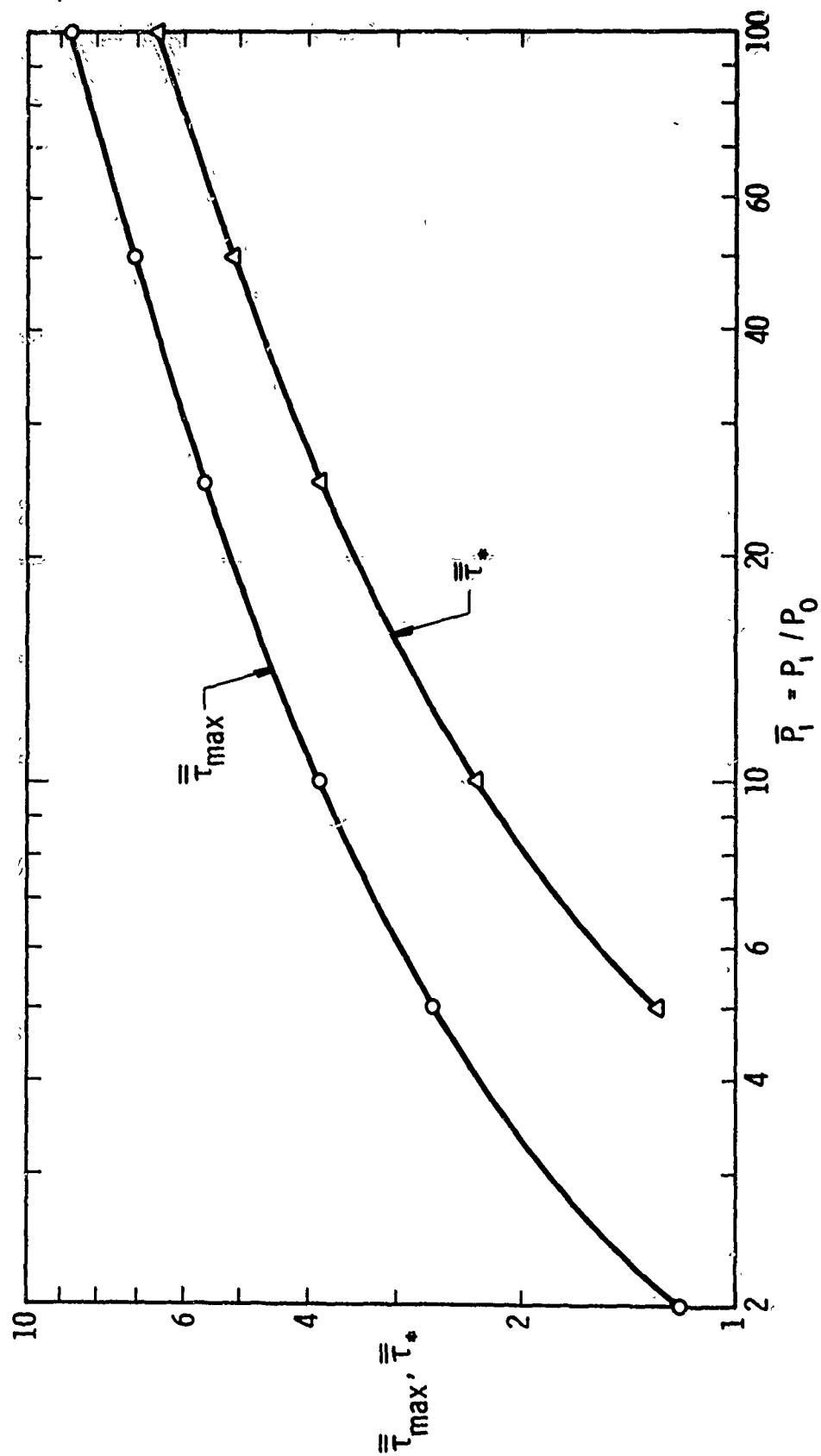
FIGURE 4. SCALED BLOWDOWN DURATIONS

III. COMPARISON WITH DATA

The function $\bar{\tau}_{max}$ can be compared with measured blowdown times for vented structures, as from Reference 3. Theoretical functional forms for $\bar{\tau}_{max}$ are plotted versus $\bar{P}_1$ in Figure 5, and data from Reference 3 cast into this form are also plotted. Because Reference 3 cites spread in measurements, we can indicate this spread by width and height of each rectangle in Figure 5. The experimental data describe a different functional form than Owczarek's theory. (Note that the vertical scale is greatly expanded, and that deviation from the theoretical curve is always within a factor of two.)

Some data are reported in Reference 5 for blowdown times for cylindrical vessels with end plates having various sizes of holes. These investigators give times to reach critical pressure, rather than atmospheric pressure. But, we can easily calculate scaled times corresponding to this pressure; they are $\bar{\tau}_*$ and $\bar{\tau}_*$, defined in the same manner as in Eqs. (12) and (16) respectively. These quantities are plotted on Figures 4 and 5. Scaled data for $\bar{\tau}_*$ from Reference 5 are shown on Figure 5 and lie generally below the experimental values for $\bar{\tau}_{max}$ from Reference 3.

A much more approximate analysis of blowdown from vented structures has been made by Kinney and Sewell.[6] They assumed that there was no regime for flow transition, and venting therefore occurred at sonic flow velocity down to outside atmospheric pressure. They also assumed an initial source temperature independent of initial pressure. These assumptions yielded a simple differential equation for pressure change,

$$\dot{P} = -C\frac{A}{V}P \qquad (17)$$

Kinney and Sewell integrated this equation directly and obtained the solution*

$$\ln \bar{P} = \ln \bar{P}_1 - \bar{C}\bar{A}t \qquad (18)$$

They chose a value for $C = 2379$ ft/sec, giving $\bar{C} = 2.130$. Using our definition for

$$\bar{\tau} = \bar{A}t, \qquad (19)$$

Eq. (18) becomes

$$\ln \bar{P} = \ln \bar{P}_1 - 2.130\bar{\tau} \qquad (18a)$$

and it yields $\bar{\tau}_{max}$ by setting $\bar{P} = 1$. This value is

$$\bar{\tau}_{max} = 0.4695 \ln \bar{P}_1 \qquad (20)$$

It is plotted on Figure 5 as the line labeled "Theory, Kinney and Sewell", and apparently gives better agreement with experiment than the more "exact" theory of Owczarek.

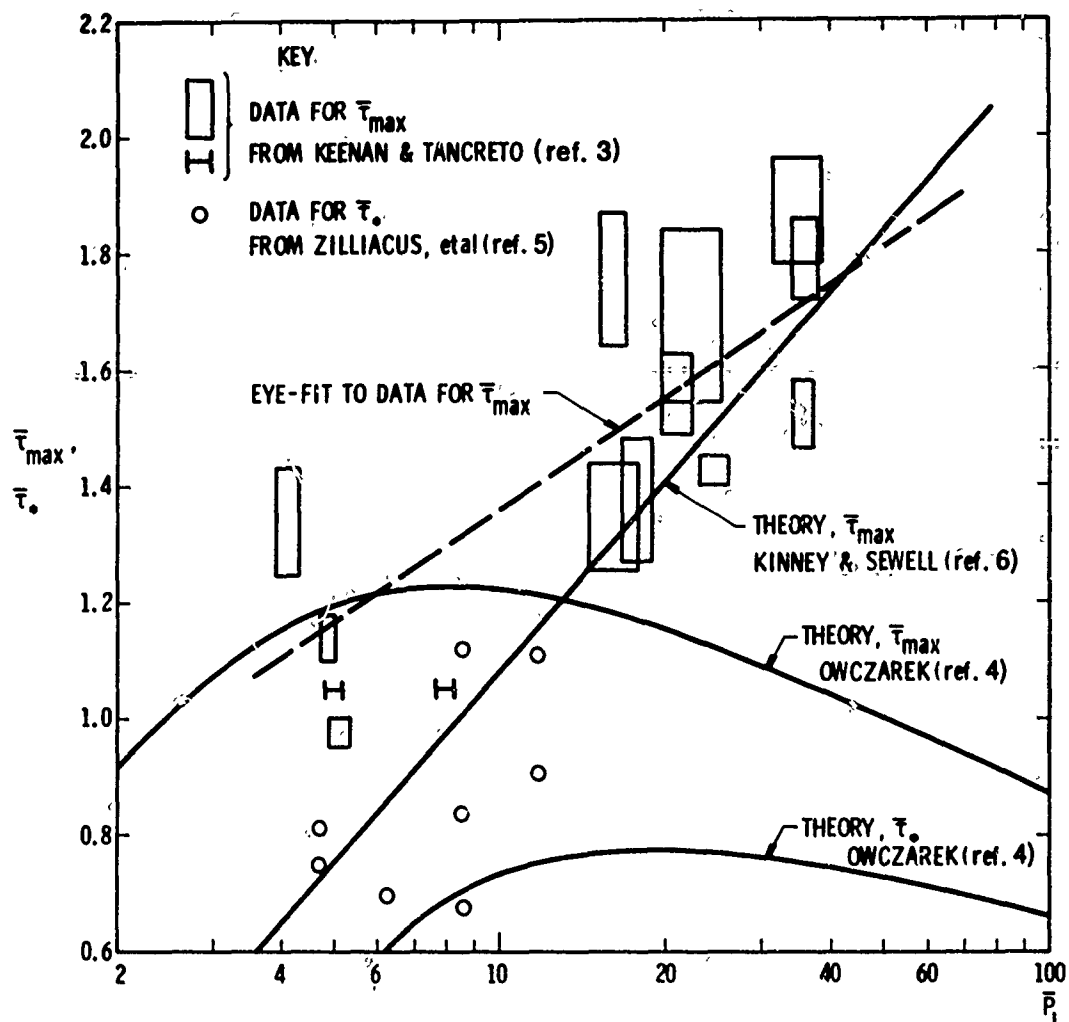*We have converted to dimensionless parameters, with $C = C/a_0$.

FIGURE 5. SCALED BLOWDOWN DURATIONS FOR SUPPRESSIVE STRUCTURES

15

Because the theories of Owczarek or Kinney and Sewell predict complete time histories of blowdown pressures, these histories can be integrated to yield predictions of gas pressure impulses, I_g. This was done graphically for plots such as Figure 3 from Owczarek's theory, and analytically for the simpler equation of Kinney and Sewell. The latter equation, in dimensionless form, is

$$\bar{I}_g = \frac{1}{\bar{C}} \left(e^{\bar{C}\bar{\tau}_{max}} - 1 \right) - \bar{\tau}_{max} \tag{21}$$

where

$$\bar{I}_g = I_g \left(\frac{\alpha_e A_s a_0}{p_0 V} \right) \tag{22}$$

Both prediction curves are shown in Figure 6, together with points from Keenan and Tancreto.[3] Again, the very approximate formula of Kinney and Sewell appears to fit the data better than the more "exact" curve based on Owczarek's equations.

IV. DISCUSSION

From the analysis presented here, it seems apparent that time histories of pressures within vented explosion containment structures can be scaled, and perhaps can be estimated, based on a simple gas dynamic analysis by Kinney and Sewell,[6] or a more complex analysis by Owczarek.[4] The scaling (dimensionless) parameters involved are

$$\bar{t} = \left(\frac{t a_0}{V^{1/3}} \right)$$

$$\bar{A} = \left(\frac{\alpha_e A_s}{V^{2/3}} \right)$$

$$\bar{P} = \left(\frac{P}{p_0} \right) \tag{23}$$

$$\bar{P}_1 = \left(\frac{P_1}{p_0} \right)$$

Owczarek's analysis predicts that

$$\bar{P} = f_1 \left(\bar{P}_1, \bar{A}\bar{P}_1^{1/2}\,\bar{t}, \gamma \right) \tag{24}$$

and gives this functional dependence (see Figs. 2 and 3 for a $\gamma = 1.4$). The combination of scaled parameters in the second term in the parentheses is also a scaled time,
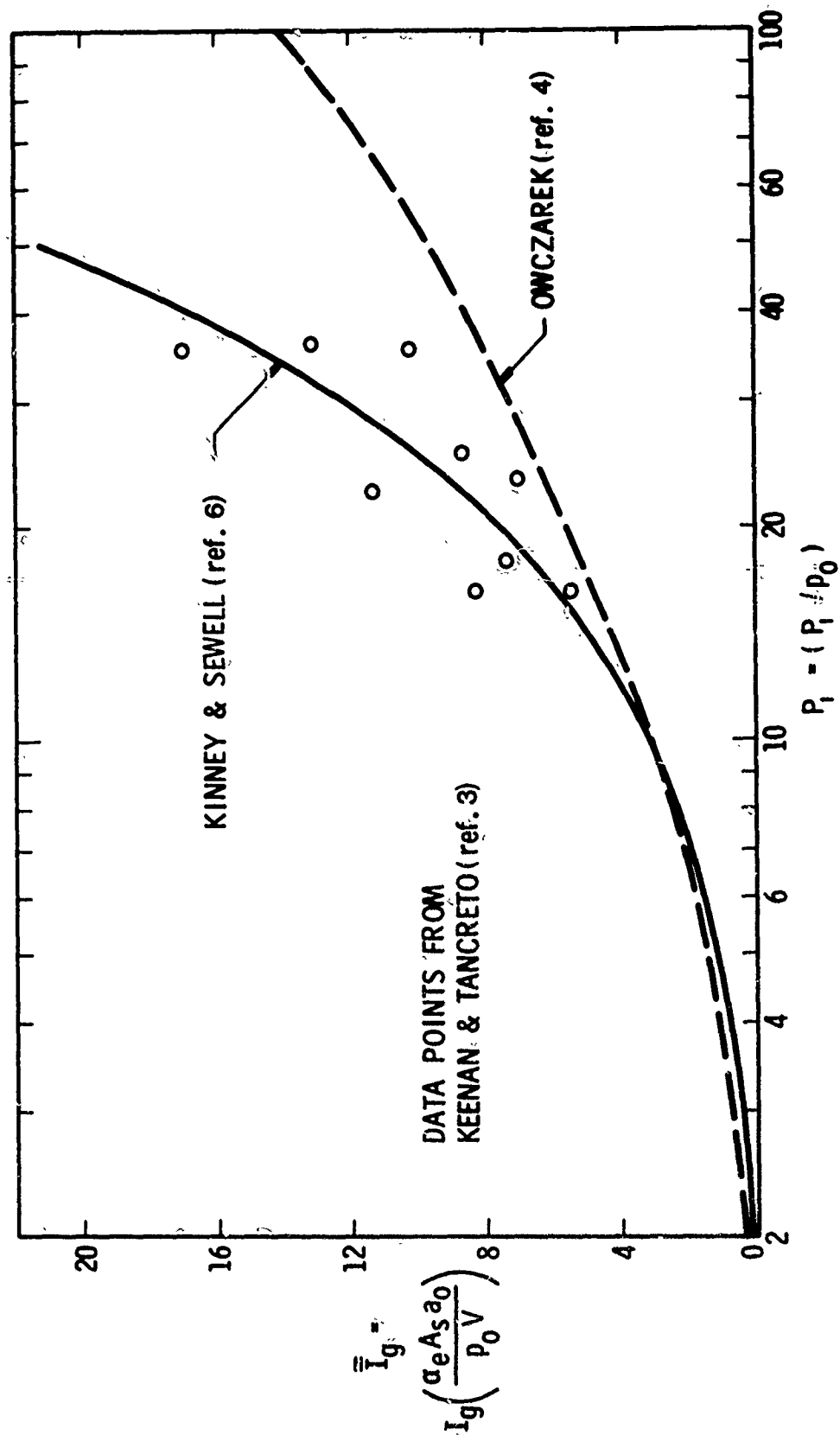
FIGURE 6. SCALED GAS PRESSURE IMPULSE VERSUS SCALED INITIAL PRESSURE

$$\bar{\tau} = \bar{A}\bar{P}_1^{1/2}\bar{\tau}'$$ (12a)

Because $\bar{P}_1$ appears in this term, a more useful scaled combination is probably

$$\bar{\tau} = \frac{\bar{\bar{\tau}}}{\bar{P}_1^{1/2}} = \bar{A}\bar{\tau}$$ (14a)

This combination also appears in Kinney and Sewell's simple analysis.

Both prediction equations predict finite blowdown durations, so maxima for $\bar{\bar{\tau}}$ and $\bar{\tau}$ can be easily calculated. These maxima and scaled times to reach critical pressure are shown as functions of $\bar{P}_1$ in Figures 4 and 5 and data from Reference 3 and Reference 5 are compared to the theoretical predictions in Figure 5. The scaled pressure-time histories can be integrated to give scaled gas impulse $\bar{I}_g$, which is plotted in Figure 6 as a function of $\bar{P}_1$. This parameter is defined as

$$\bar{I}_g = I_g \left(\frac{\alpha_e \bar{A}_s a_0}{p_0 V} \right)$$ (25)

Limited experimental data indicate better agreement with the simple equation of Kinney and Sewell than with the more exotic solution of Owczarek. Both, of course, are approximations to the complex situation occurring during venting.

V. CONCLUSIONS

More venting pressure data should soon become available from BRL tests in the Applied Technology Program. Also, conversations with J. Proctor of NSWC White Oak indicate that there is a body of Norwegian data not noted here. NSWC is also looking at the venting process in much more detail. For these reasons, curves such as Figures 2 and 3 should be considered as *tentative*, and should only be used for interim estimates of venting pressures, gas impulses, and durations. We feel that the primary value of the information presented in this report lies in development of an improved method of presentation of venting data in dimensionless form, and in presentation of some curves and formulas which give *preliminary* estimates of venting for structures with large vent area ratios.

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